# New contributions for the revision of colour rendering for light sources based on the colour gamut volume

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**ABSTRACT:**

As the current proposed colour rendering algorithm by CIE needs a reference illuminant for each test illuminant or light source, we propose an alternative procedure for calculating the colour rendering index of illuminants and light sources, which is based on the computation of the total number of distinguishable colours inside the associated colour solid. Therefore, the new colorimetric quality index among light sources would be absolute, with no need for using a reference illuminant.

Once that we have done this study, we have checked that the total number of distinguishable colours depends on the spectral content of the light source and also there is a good correlation , although it is not linear, between our method and that one associated to CIE.

**Key words:** Colorimetry, Colour Discrimination, Illuminant, Light Source, Colour Rendering,

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## 1. Introduction

Since the human colour perception is essentially tri-variant all distinguishable colours by the human visual system are distributed in a 3D structure named colour solid. The colours delimiting the borders of the colour solid are named optimal colours and they were exhaustively studied by D.L. MacAdam[1-2] in 1935, so the frontiers of the colour solid are also named MacAdam limits. The shape of the Rösch-MacAdam colour solid does not vary only depending on the colour space, but also depending on the illuminant or light source. In a recent work[3] we have demonstrated that, even in the more uniform colour spaces (CIECAM02, DIN99d, etc), the shape and volume of the colour solid change with the illuminant or real light source. The greater colour solid volume, the greater the number of distinguishable colours that is, the colorimetric rendering or quality index is better. Therefore, estimating the number of distinguishable colours can be an alternative for the current algorithm of the colour rendering of light sources published by CIE[4].

This colorimetric quality index for light sources is relative because a reference illuminant is always needed for each test lamp. Given a test lamp and the spectrum, the Colour Temperature is calculated. Then, the reference illuminant for light sources with correlated colour temperature below 5000 K shall be a Planckian radiator and from 5000 K one daylight phase. It is necessary to do a chromatic adaptation transform between the reference illuminant and the test lamp.

Once the illuminant or light source has been characterized, it is calculated the colour difference between a pair of corresponding colours (a colour chip illuminated under the test lamp and the reference illuminant).

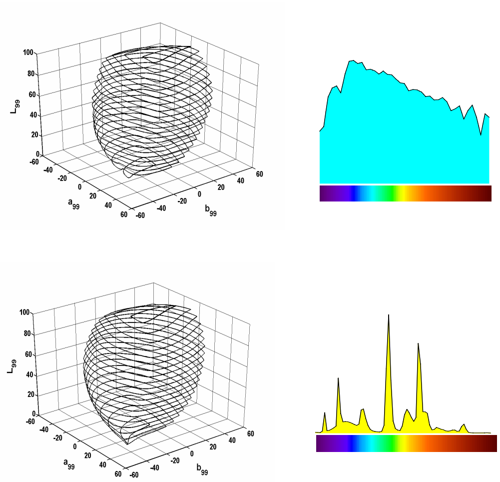
In this work we show several methods for the computation of the total number of discernible colours. In the two first methods we firstly calculate the number of distinguishable colours in constant lightness planes of the colour solid, and accumulating the partial counts for each lightness plane we can compute the total number of the distinguishable colours. The other methods calculate the total volume the complete colour solid.

Therefore, selecting some illuminants and light sources we can compute the total number of associated distinguishable colours. These results establish an absolute ranking of colour rendering, unlike the current CIE colour rendering algorithm. In this work we make a comparison between a set of illuminants (A, C, D65, F2, F11, P100, D100, FL3.1, FL3.5) and light sources (HP1,3) published by CIE[5], and their colour rendering is evaluated using the proposed methods and also the standard procedure, which is not based on the computation of the discernible colours.

## 2. Method

As in this work we propose a new algorithm based on the computation of the total number of distinguishable colours inside the associated colour solid, first we have to calculate the complete associated colour solid for any illuminant or light source. For this reason, we have developed an improved algorithm from the original MacAdam's algorithm to calculate the optimal colour or the MacAdam limits, which are the borders of the colour solid. With this new algorithm we can calculate the complete associated colour solid for any colour space, for instance, in CIECAM02 or DIN99d, and for any illuminant and light source and we can calculate the colour solid with a high resolution using constant lightness planes, from 1 to 100, with lightness step equals to one.

So, the question of how many colours, with a given illuminant or light source, we can distinguish, it can be answered making simultaneous comparisons of colour solids under several illuminants or lamps, but taking into account a chromatic adaptation. In this case we have used the CAT02 transform of the CIECAM02 colour appearance model[6]. In the figure number we show several colour solids for the illuminants D65, a fluorescent illuminant called F11 and for the high pressure lamp (HP1). But we have used the DIN99d colour space[7] because it is more coherent to show corresponding colours in a different colour space to that associated to one colour model, which describes and applies a chromatic adaptation transform CAT02.



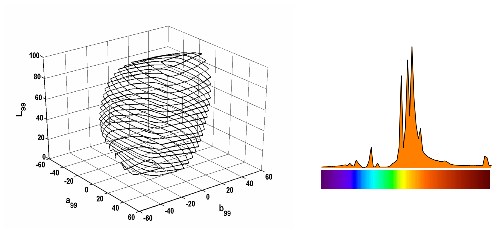


Fig.1. Colour solid in adapted DIN99d colour space for the illuminants D65 (top), F11 (centre) and the lamp HP1 (bottom) and their spectral content.

After this comparison, it is clear that the shape and volume of colour solid depends on the spectral content of the illuminant/light source.

In this work, we have developed several methods for calculating the number of distinguishable colours inside the colour solid. The first method consists in computing the partial counts of distinguishable colours for each constant lightness MacAdam locus encoded by adapted DIN99 colour space, with a lightness step $\Delta L^*=1$, from 1 to 100, by a squares with unity area inside each MacAdam locus. In each constant lightness plane, the packing algorithm draws the first square around the achromatic point and next successive non-overlapping squares are drawn from the first square. In this way, the sum of these partial counts from $L^*=1$ to 100, gives the total number of distinguishable colour under each illuminant/light source.

The second method is named ellipses packing. This takes the Krauskopf & Gegenfurtner's[8] discrimination model into account, based on psychophysical data. It works by filling the constant lightness MacAdam loci, previously transformed by the CAT02 transform under illuminant E, with discrimination ellipses increasing in area with increasing distance from the achromatic point in a modified MacLeod-Boynton chromaticity diagram. Consequently, again accumulating the partial counts of non-overlapped ellipses or distinguishable colours for each constant lightness MacAdam locus from 1 to 100, we can estimate the total number of distinguishable colours inside colour solid for any light source.

Other method to calculate the number of distinguishable colours is the tetrahedron packing[9]. This method is based on split the colour solid in tetrahedron; calculate the volume of each tetrahedron and the total sum of volume of each tetrahedron is the volume gamut. An alternative method, with similar results, consists in using the convex hull function by MATLAB for constant lightness MacAdam loci.

## 3.Results

Firstly, Figure 2 shows an example of a MacAdam locus packed with squares. The number of discernible colours obtained with this method is very large, so the visualization of the MacAdam loci filled with squares with unity area is not easy. We have shown the results for a lightness plane equal to 30 for the illuminant D65.

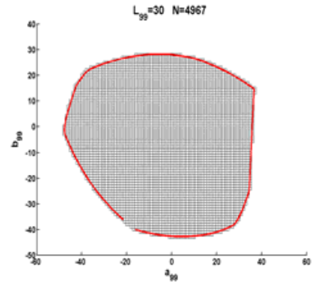



Fig.2. Packing with squares of unity area of the MacAdam locus for the lightness plane $L^* = 30$ under illuminant D65 in the DIN99d chromaticity diagram.

Now, we show an example for the packing of MacAdam loci with ellipses for the illuminant D65 at constant lightness equal to 30. Working with the ellipses packing method the number of distinguishable colours is smaller than with the squares packing method.

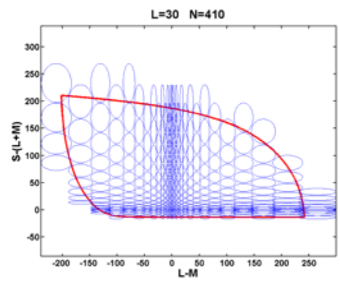



Fig.3. Packing with ellipses of the same constant lightness ($L^* = 30$) MacAdam locus in the modified MacLeod-Boynton's chromaticity diagram for the illuminant D65.

For these methods, the number of distinguishable colours, *N*, for each constant lightness plane and illuminant/light source can be obtained calculating the area beneath each curve plotted in Figure 4.

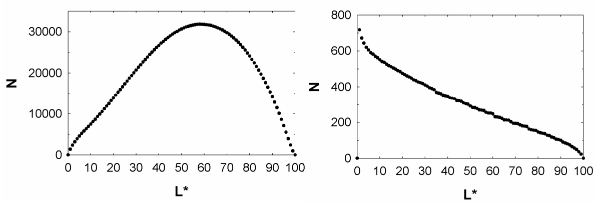



Fig.4. Partial counts of discernible colours vs. lightness value for the illuminant D65 taking into account both packing methods: squares (left) and ellipses (right).

In the next figure, we show the complete colour solid split in tetrahedron. This method has been developed following the steps the technical report TC 8-05. We obtain similar results with this method and with convex hull packing.

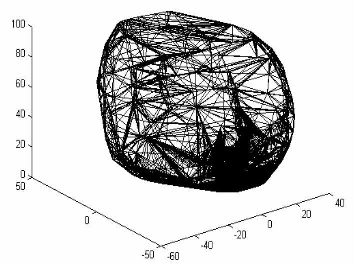


Fig.5. Packing with tetrahedron of complete colour solid associated to high pressure lamp (HP1).

Next, it is interesting to make a comparison of the obtained with different illuminants, light sources and the used packing methods with respect to the standard CIE colour rendering algorithm[4]. It is important again to remember that the standard CIE colour rendering index ($R_a$) is a relative colorimetric quality index because each test illuminant or light sources can have a different reference illuminant. In contrast, all proposed methods try to establish an absolute colorimetric quality index without the need to establish a reference illuminant and to calculate colour differences between a corresponding colour pair, and only calculating the volume of the associated colour solid.

TABLE I

Total number of the distinguishable colours of several illuminants and light sources according to all packing methods of the constant lightness MacAdam loci

| Light source | Ellipses | Squares | Tetra | Convex hull | $R_a$ (CIE) |
|---|---|---|---|---|---|
| A | 0.25 e5 | 0.50 e6 | 0.47 e6 | 0.49 e6 | 99.58 |
| C | 0.33 e5 | 0.54 e6 | 0.51 e6 | 0.52 e6 | 97.39 |
| D65 | 0.31 e5 | 0.53 e6 | 0.50 e6 | 0.52 e6 | 99.58 |
| F2 | 0.30 e5 | 0.44 e6 | 0.51 e6 | 0.43 e6 | 62.83 |
| F11 | 0.26 e5 | 0.49 e6 | 0.46 e6 | 0.48 e6 | 82.91 |
| HP1 | 0.22 e5 | 0.39 e6 | 0.37 e6 | 0.38 e6 | 8.29 |
| HP3 | 0.25 e5 | 0.49 e6 | 0.46 e6 | 0.48 e6 | 82.50 |
| P100 | 0.35 e5 | 0.54 e6 | 0.53 e6 | 0.53 e6 | 97.38 |
| D100 | 0.35 e5 | 0.55 e6 | 0.53 e6 | 0.53 e6 | 99.22 |
| FL3.1 | 0.33 e5 | 0.47 e6 | 0.44 e6 | 0.43 e6 | 51.28 |
| FL3.5 | 0.31 e5 | 0.52 e6 | 0.49 e6 | 0.51 e6 | 94.93 |

As you can see in the table I, in spite of the fact that the differences displayed in the colour solids in DIN99d or in the MacLeod-Boynton colour space are small, the total number of distinguishable colours varies from one to two thousands. Secondly, the best colorimetric performance is for the Planckian illuminant with 100,000 colour temperature and the worst result is for the high pressure lamp 1. The correlation among the four colorimetric methods for classifying illuminants and light sources is very good, although it will be never linear.

Finally, we can say some ranking positions coincide with the standard criterion established by CIE, above all for the low portion of the used ranking value.

## Conclusions

A new method for classifying the colorimetric quality of light sources can be considered equal to that of CIE method. This new method proposes an absolute colorimetric comparison among illuminants and light sources. With this new algorithm, the illuminant P100 is the best one and the high pressure lamp HP1 is the worst one of this comparative.

On the other hand, all methods, proposed for computing the number of distinguishable colours, are approximations to the precise calculation. Working with the squares packing methods in DIN99 colour space, the obtained final result is always by excess. And working with the ellipses, tetrahedron and convex hull packing method, the obtained final result is always by defect. Consequently, what we suggest is a re-calculation with a spheres packing algorithm in adapted DIN99 colour space or in a CIECAM02 colour space, in order to compute the total number of distinguishable colours inside the colour solid.

For these reasons, we are sure the main conclusion of this work is clear; the total number of distinguishable colours depends on the spectral content of the light source.

Finally, we suggest some potential applications of our work. For instance, we can use our methodology to compare gamut volumes for colour reproduction technologies, including colour imaging devices. And, besides, in the lighting design in sports, museums, TV, cinema, [10] etc.

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